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POLYMER COMPOSITE-BASED VIBRATION AND NOISE EMISSION CONTROLS FOR HAND-STRUCK IMPACT TOOLS

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ABSTRACT

Exposure to high noise levels may be the most common occupational hazard. Recent estimates suggest that as many as 30 million Americans are exposed to noise levels greater than the current safe limits for workplaces. At current durations of exposure, it is expected that 25% of these workers will develop permanent, noise-induced hearing loss. In many of these industrial environments, high levels of vibration also exist that can lead to several injuries and ailments. To address the adverse effects associated with the use of high noise emission impact tools, a study was initiated to develop and evaluate alternate tool designs that reduce the potential for hearing loss and vibration-related injuries. Recent work has focused on integrating advanced engineering polymers (composites) into tool designs for the purpose of eliminating direct metal-to-metal impact. This approach has several significant performance advantages including reduced operator discomfort due to hand-arm mechanical shock, reduced noise, and less danger from flying metal fragments. To quantify sound emission characteristics of these new designs, continuous sound pressure, maximum sound pressure, and maximum sound pressure level were measured using an array of five precision microphones each located 1 meter from the tool. Data was sampled at 40 kHz while test subjects operate both pneumatic tools and hand-struck tools. Frequency spectra of the sound pressure signals were examined for all tool treatments, and indicate that the addition of a polymer insert between metal impact components significantly reduces noise emission, especially at higher frequencies. Similar reductions were observed in vibration transmission in the hand and arm. As a result, tools that integrate polymer-based components may be operated for longer daily exposure times without inducing hearing loss or vibration-related injuries. Data from this study may also help auditory and ergonomic specialists in understanding impulse noise characteristics and exposure.

KEYWORDS

Hand-struck tools, engineering polymer, impact, finite element model, vibration.

INTRODUCTION

The use of hand-struck tools is an integral part of many industries throughout the world. In fact, many jobs require frequent and often continuous use of these devices. Injuries in the workplace resulting from these tools have been studied extensively, and have been classified as single-incident or cumulative trauma. (1) Single-incident occurrences are often attributable to a one time misuse or overexertion. The factors that contribute to this type of trauma include the tool type and design, the workplace environment, and the skill and fatigue of the operator.

The causes and resulting effects associated with cumulative trauma are much more complex than single incident circumstances. Several studies have demonstrated a link between exposure to the vibration from tools and various injuries including vibration induced white finger, hearing loss, and Hand Arm Vibration Syndrome (HAV). (2, 3, 4, 5, 6) These ailments have been estimated to be prevalent in several industries, and pose a growing concern to the long term health of workers worldwide. In a study of more than 400 chain saw operators, symptoms of HAV were found in 11.7% of workers with 20 to 24 years of exposure, and 20.9% of works with more than 30 years of exposure. (7) An evaluation of 52 studies across several different industries with occupations that included hand and arm vibration exposure found that 43 studies reported worker incidence rates of injury of more than 20%. (8) In the United Kingdom, more than 1.2 million men and 44,000 women were determined to be exposed to daily levels of vibration that exceeded the suggested daily levels. (9) The resulting economic consequences of vibration-related injury have been estimated to be substantial. In 1986, the cumulative costs of hand tool injuries were approximated at $10 billion annually. (10)

In light of the problems associated with the use of hand tools, a study was initiated to evaluate the performance of conventional hand-struck tools and develop improved designs that can mitigate some of the detrimental effects associated with their long-term use. The initial focus of the work was on improving cold chisel designs used for cutting metal.

LITERATURE REVIEW OF HAND TOOL RESEARCH

The design of hand struck tools and the materials and methods used to manufacture them have evolved very little historically. Most tools are still manufactured from medium to high carbon steel, and the basic configurations of typical hand struck tools including chisels and punches have remain unchanged for centuries. Most work in recent decades has focused on improved designs for power tools, and is driven by their larger market presence and value compared to hand struck tools. Power tool research is diverse and includes quantifying the magnitude of vibration emanated from common tools, determining the factors that influence the transmission of vibration energy to the user, and improved designs and devices that reduce the vibration and forces exerted on the hand and arm. This work has resulted in power tool designs that reduce the vibration energy transmitted to the user (11), as well as several innovations including anti-vibration gloves (12), air-bladder technology (13), and vibration attenuating handles. (14)

Other studies that have possible relevance to hand-struck tool improvements have modeled and tested hand-arm-tool systems. Kihlberg (15) found that exposures with frequencies less than 50 Hz caused a greater load on the elbow and shoulder while exposures above 100 Hz, typical of impact tools, induced greater loads on the hand and fingers. Other studies have also shown that more energy is transferred to the hand under impact (16, 17), and models have predicted that the higher frequency energy induces higher stresses in the fingers and ultimately dissipates in the hand palmar tissues and may be one cause for the incidence of vibration-induced whiter finger. (18, 19)

OBJECTIVES OF THIS STUDY

The overall goal of this work is to improve conventional hand-struck tool designs in order to reduce the detrimental effects associated with there long term use. Furthermore, our intent is to achieve these improvements without sacrificing tool performance and utility. For the purposes of this study, the focus is on hand-struck tools with an emphasis on steel chisels used for cutting metal. The specific objectives are to model the hammer-tool system, and evaluate through modeling and testing possible improvements. Possible improvements to be examined include the integration of non-traditional materials like advance engineering polymers into chisel designs.

Modeling and Analysis of the Force Transmission Characteristics of a Chisel with a Polymer Cap

To understand the behavior of a hammer-chisel system during impact as well as the design requirements of the cap illustrated in Figure 1, a simple lumped-mass model to predict the force the chisel imposes on the work was developed. This force depends on a number of system components including: hammer weight and velocity; chisel parameters; and polymer cap parameters. A relatively simple lumped-parameter model was used. In spite of its simplicity, this model permits inclusion of all the pertinent inputs and outputs.

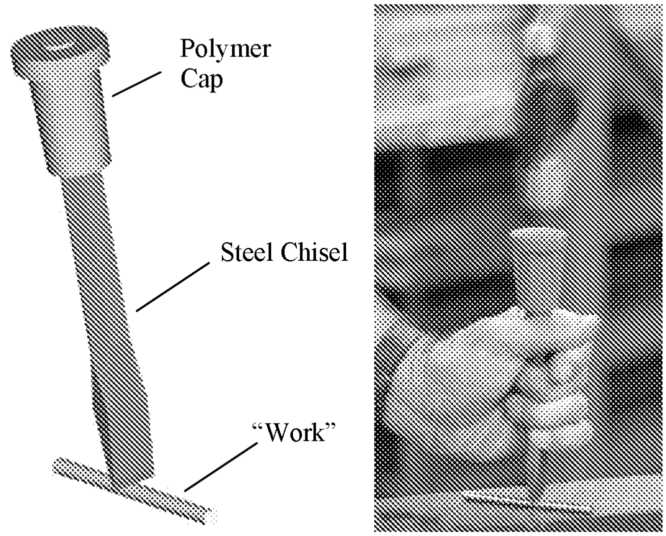


Figure 1. Conceptual view and prototype of a conventional steel chisel fitted with a reinforced polymer cap.

Force Transmission Model Description. A lumped-parameter model was used, and consisted of four simple elements, two masses and two springs. These idealized computational elements simulate the actual components. In all cases, only forces and displacements in the axial direction are included.

For the model shown in Figure 2, Mass 1 is an element that simulates the hammer. At time=0, the hammer, moving at V, just impacts the top of the chisel cap. Spring 1 is an element

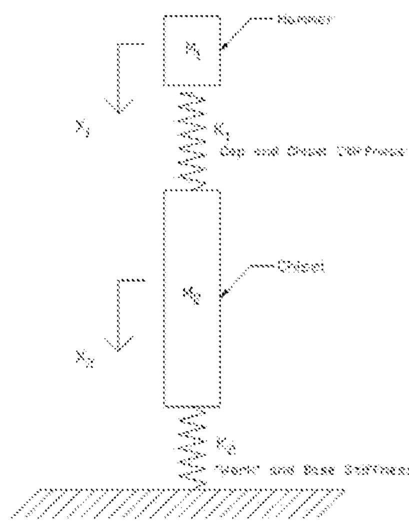


Figure 2. Spring mass model of the hammer-chisel system that includes a chisel cap.

that simulates deformation of the cap and the chisel itself. Its spring constant is that of a series combination of the cap and chisel. Mass 2 is an element that simulates the chisel. Note that this mass is important because it’s inertia causes the force below the chisel to be different from that on top. Usually, the force under the chisel is lower than that on top. Spring 2 is an element that simulates the deformation of two things: the chisel

into the work and the deflection of the support under the work. In actual usage, the support under the work is very rigid. However, in experiments with a force gauge under the work, that stiffness needs to be included. The spring constant of this element is a series combination of both effects.

Using the model illustrated in Figure 2, a relatively simple analysis was made using the following basic differential equations with the indicated boundary conditions,

$$\ddot{x}_1 + \frac{k_1}{m_2}x_1 + \frac{k_2}{m_2}x_2 = 0 \qquad (1)$$

$$\ddot{x}_2 \quad \frac{k_1}{m_2}x_1 \quad \left(\frac{k_1 + k_2}{m_2}\right)x_2 = 0 \qquad (2)$$

$$x_1(0) = x_2(0) = \dot{x}_2(0) = 0$$
$$\dot{x}(0) = V \qquad (3)$$

Simulations. The equations were solved using Matlab™ Software. To do this, the differential equations were rewritten in vector form in term of a four-component vector.

Most input parameters were determined by direct measurements. Only one parameter was adjusted – the effective spring constant of the chisel penetrating the work. This parameter was adjusted from measured chisel force to a value of 70.1 MN/m (.4 M lb/in). The complete set base case parameters is:

- Effective Hammer Weight = 9.21 N (2.08 lb) [computed from hammer and instrument arm weight]
- Chisel Weight = 2.69 N (.605 lb)
- Polymer Cap Diameter = 12.7 mm (.5 in)
- Chisel Effective Diameter = 16.8 mm (.661 in)
- Polymer Cap Thickness = 5.08 mm (.2 in)
- Chisel Length = 102 mm (4 in)
- Polymer Modulus = 1.90 GPa (.275 Mpsi)
- Steel Modulus = 207 Gpa (30 Mpsi)
- k2a = Cutting spring constant = 70.1 MN/m (.4 M lb/in)
- k2b=Base spring constant = 105 MN/m (.6 M lb/in)
- Hammer Velocity (ft/sec) = 5.64 m/sec (18.5 ft/sec)

A number of relations were computed with these values as well as a number or excursions. The next sections describe these computed results.

Chisel Force During an Impact. Force vs. time is plotted on Figure 3 for a bare, uncapped chisel and on Figure 4 for a polymer capped chisel. In each case, the forces are shown on top and bottom of the chisel. The force on the bottom is designated as the chisel force since it acts on the material being cut. The force on top does not equal that on the bottom because of the chisel inertia.

These graphs show that there are two dominant frequencies for the chisel force. For both bare and capped, the two wavelengths are approximately .3 and 1.2 msec. The maximum chisel force is only somewhat higher in the bare chisel; and, in the bare chisel, the force on top is significantly higher than that on the bottom.

Effect of Polymer Modulus on Maximum Force. An important factor in designing a capped chisel is to determine the effect of polymer properties on performance. Since we assume that maximum chisel force is the key variable affecting performance, we computed the relation between this variable and polymer modulus and the results are plotted on Fig 5. The experimental data plotted will be discussed in a later section. Maximum force is plotted against the polymer modulus divided by that of steel. A log scale is used to include the range of available polymers.

As expected, this computation shows that increasing polymer modulus increases the maximum chisel force. The reason for this effect is apparently the shorter, sharper impact with high modulus materials. The slope of the force-modulus relation is high for low modulus materials and relatively low for high modulus ones.

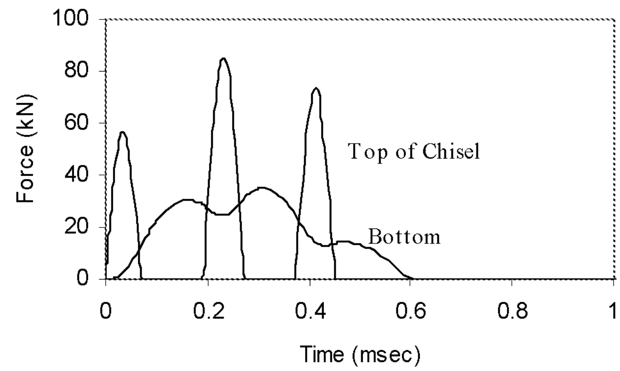


Figure 3. Computed force vs. time for a bare chisel.

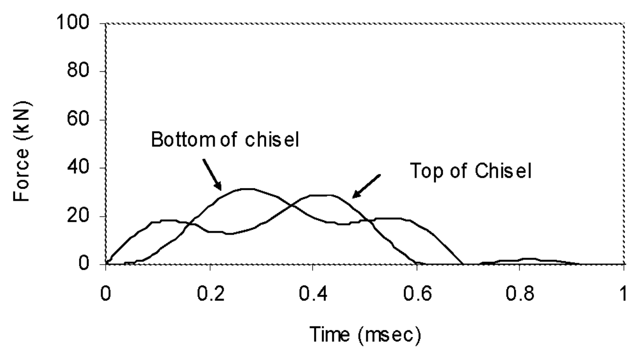


Figure 4. Computed force vs. time for a capped chisel.

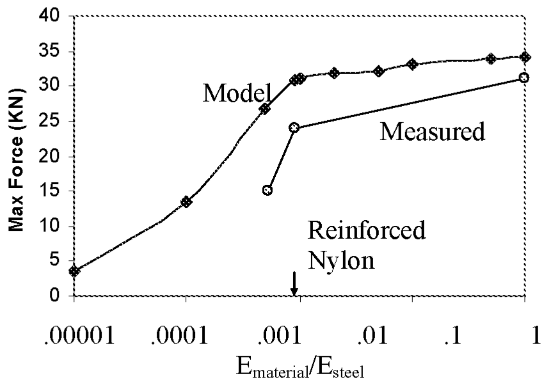


Figure 5. Effect of cap modulus on the maximum chisel force.

Note that this functional relation is not as smooth as might be expected. This occurs because of the oscillating nature of the force-time relation. In some cases the maximum force develops in the first cycle and sometimes on a later cycle. When the cycle that has the maximum force changes, the Fmax vs. E curve tends to be jagged. This effect occurs in most of the functional relations with system parameters.

Two important findings come from this relation. First, higher modulus polymers result in higher forces – as would certainly be expected. Second, high modulus polymer caps produce a maximum force relatively close to that of a bare chisel. This second finding is of great importance for the cap design.

Effect of Cap Thickness. The effect of cap thickness was computed and plotted on Fig 6 in terms of maximum chisel force vs cap thickness. The zero thickness level corresponds to a bare chisel. The experimental data on this plot will be discussed in a later section.

This relation is similar to the modulus effect on Fig 4 in that increased compliance reduces maximum chisel force. Compliance increases with thickness and decreases with modulus.

As explained in the previous section, this relation is jagged because the maximum force occurs at different cycles.

An important result of this computation is that chisel force does not fall sharply with increasing thickness. This is important in the development of a useable cap since relatively thick caps (>= 5 mm) are needed to avoid polymer failure.

Effect of Hammer Weight and Impact Velocity. Increasing either the hammer weight or impact velocity certainly increases chisel force. The model was used to compute the extent of this effect for a capped chisel and the results are plotted on Figure 7. As in the other plots, the base case parameters are used – except for the designated variations.

This result shows that the relation between force and impact velocity is essentially linear. Although the kinetic energy of hammer increases with the square of the velocity, the maximum force increases only with the first power.

Increasing hammer weight increases maximum chisel force. The rate of increase is significantly less than linear.

Effect of Other System Parameters. This model can be used to determine the effect a number of other parameters describing the materials or chiseling operation but for the sake of brevity, additional plots are not included. Parameters related to the compliance under the chisel can be quite important. Stiff supports under the work can increase force significantly – an effect well know by mechanics.

Another important effect occurs when the chisel cuts into the work. During this process, the compliance under the chisel increases as it becomes progressively harder to increase the amount of cut material. This increase in compliance under the chisel increases the force as was indeed observed by force measurements, but not computed because the cutting compliance change was not known.

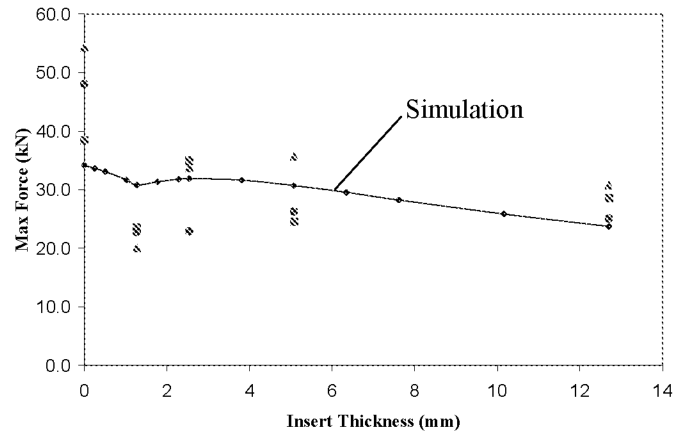


Figure 6. Predicted and measured maximum force exerted on the work piece during a hammer impact vs. cap thickness. Measured values are an average of 3 replicates.

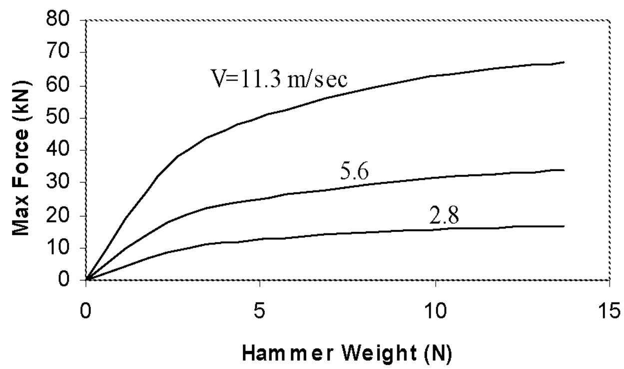


Figure 7. Predicted effect of hammer weight and velocity on maximum chisel force exerted by a capped chisel.

Cap Material Selection

We found that selecting the correct polymer is a critical part of developing a new capped chisel. Three factors are critical: performance, durability, and cost. Each of these is described briefly in the following sections.

Modulus. The performance of a chisel depends on the force transmitted through the chisel to the work. This force and

its relation to the system parameters are described in detail in the modeling and experimental sections, and the key results are plotted in Figure 5. As shown, high polymer modulus is needed to achieve a high chisel force. When the modulus exceeds about 1/20th the level of steel, the effect is small, but when it drops below that level, chisel force drops sharply.

The modulus of polymers varies through a wide range, depending on chemical composition and processing methods. In addition, many polymers can be reinforced with higher modulus materials to create composites with enhanced properties. This is done with continuous fibers (advanced composites) and with short fibers and/or minerals (engineering polymers).

We focused our efforts on short fiber and mineral reinforced materials because they provide increased modulus and much lower cost than advanced composites. Also, they can readily be manufactured into shaped parts.

Impact Resistance. This application requires materials of very high impact resistance that withstand repeated blows of several thousand pounds each. Impact resistance is typically determined by measuring the amount of energy required to propagate a crack through a material. A standard test commonly used for this purpose is the Izod test. In this test a sample is notched (optionally) and then impacted by a swinging pendulum apparatus.

Impact resistance of polymers generally increases with break elongation. Brittle materials tend to have low elongation and low impact resistance while elastomeric materials, such as Hytrel™, have high elongation and high impact resistance. Since modulus generally varies inversely with elongation, low modulus materials usually have high impact resistance. Unfortunately, in this application, a high modulus is needed to develop a high force under the chisel. A compromise is needed between low modulus, high impact strength materials and ones with high modulus and low impact resistance. We focused on nylon polymers because of their well-established durability and high impact resistance.

Manufacturing. In low price items such as cold chisels, manufacturing costs become critical. They affect the material selection in two key ways: material costs and processing costs. Furthermore, in projects with limited business projections, resources are limited and only readily available materials can be considered.

Relative to processing, plastics divide into two categories: thermosetting and thermoplastic. When processing thermosetting resins into parts, a chemical reaction is needed to complete the cross-linking of polymer chains. This complicates the process in terms of materials storage (shelf life limitations) and requirements on process control. Thermoplastics, on the other hand, are available as pellets. They are simply melted and injected into molds of the appropriate shape.

Processing quotes were obtained from several vendors and thermoplastics were found to be significantly less costly than thermosets for this application. Thermoplastic disadvantages that were considered include relatively high mold cost (due to pressure requirements) and higher material costs.

Specific Material Selection. Using the above considerations and a number of preliminary tests, we selected the appropriate polymer material. We did not do an extensive evaluation of many materials, but rather, we assembled available information and made an engineering judgment to select the starting material. Also, we selected a manufacturing process that could readily accommodate alternate materials should they be needed.

Based on manufacturing costs, we selected the thermoplastic process route. The key factors which led to this decision were process simplicity and fast cycle time. A number of simple hammer impact tests were conducted on a range of thermoplastics, including: elastomers (Hytrel™ family), polyacetal (Delrin™), carbon fiber reinforced materials, polyesters, and nylons. Most materials failed readily after only a few blows. Nylon was considered as the primary candidate because of its demonstrated durability, high impact strength, and reasonable cost. Nylon's modulus is relatively low compared to other materials, but it can be increased substantially by adding reinforcing material.

DuPont manufactures a number of reinforced nylon polymers within the Minlon™ family of products. As with most polymers, the modulus and impact resistance vary inversely with each other. We selected an intermediate level of both properties.

Effect of Cap Thickness. Three sets of caps were fabricated at several different thicknesses and tested with a hammer test instrument (Figure 8), and the results are summarized in Figure 9. Generally, the measured values of peak force were consistent among the replicates, and

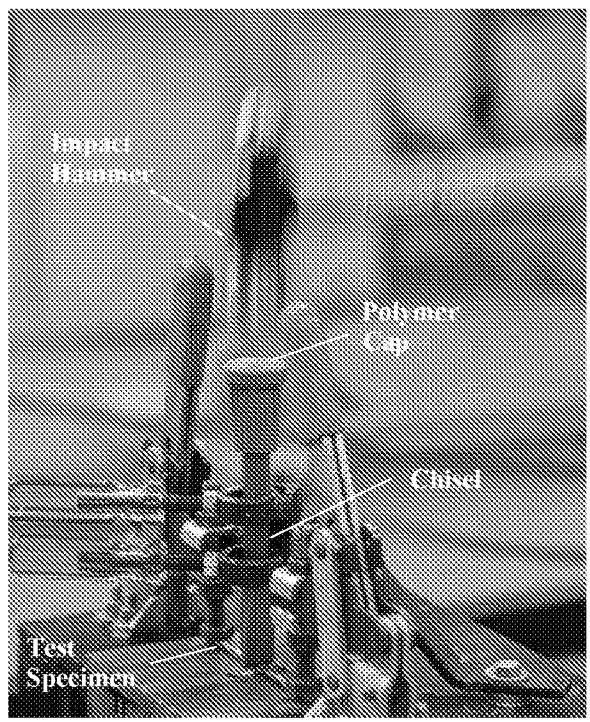


Figure 8. Chisel and cap installed in the test instrument used to evaluate various chisel and polymer cap configurations tested during this study.

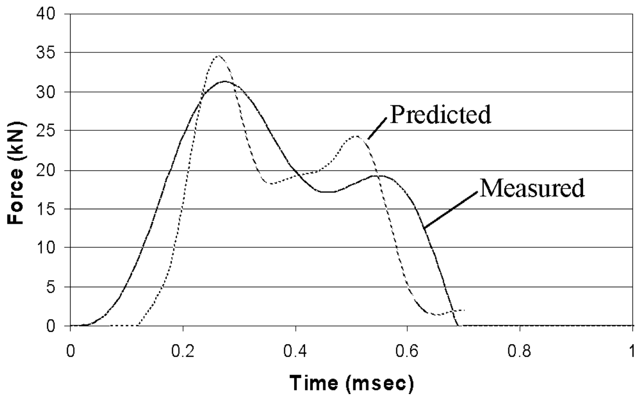


Figure 9. Measured and predicted force exerted on the test specimen by the chisel. Sampling rate = 100kHz.

very similar to the simulation results. As expected, the results show that increasing thickness reduces chisel force with a sharper drop for low thicknesses.

Effect of Chisel Tip Angle. Additional tests were conducted to assess the potential of reducing the chisel tip angle. Since the cap did reduce the peak force exerted on the chisel, sharpening the tip angle could be used to compensate for the change in force without sacrificing cutting efficiency or chisel life. Trials were conducted at chisel tip angles of 60° and 65° with both a bare chisel and a chisel with a 5.08 mm thick

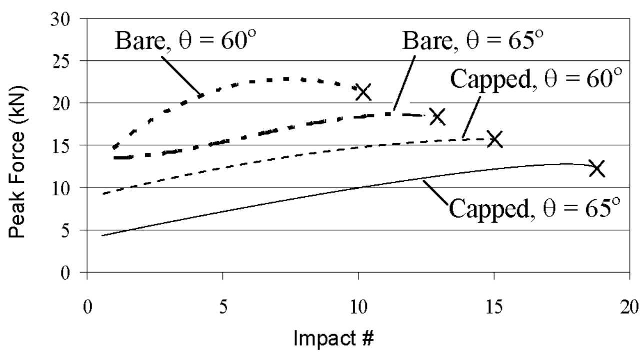


Figure 10. Peak force exerted by the chisel vs. chisel age for the capped and bare chisels at different chisel tip angles.

Minlon cap. Peak force for each impact during the cutting of a test specimen is plotted in Figure 10. The fact the sharper cutting angle resulted in higher peak forces was somewhat surprising and cannot be fully explained. One might expect the sharper tip to cut easier and therefore generate lower forces. Alternatively, the areas under the curves in Figure 9 could be viewed as a measure of energy input to the test specimen. Since the sharper tip cut the specimens with a fewer number of impacts, the energy per impact would need to be higher assuming the damage volume in the test specimen is about the same. Therefore, the peak force would be higher. More research is needed to fully understand this phenomenon.

Measurements of the number of impacts required to cut the standard specimen for different chisel configurations are summarized in Figures 11 and 12. These results indicate that a chisel with a combination of the Minlon cap and sharper chisel angle of 60° performs about the same as a conventional bare chisel with a standard 65° angle.

Durability Measurements. Using the cyclic testing device shown in Figure 8, long-term tests in which the capped chisel was hit repeatedly were used to assess the durability of the capped chisel. Results indicate a Minlon cap is capable of withstanding over 2000 dead-center impacts without failure,

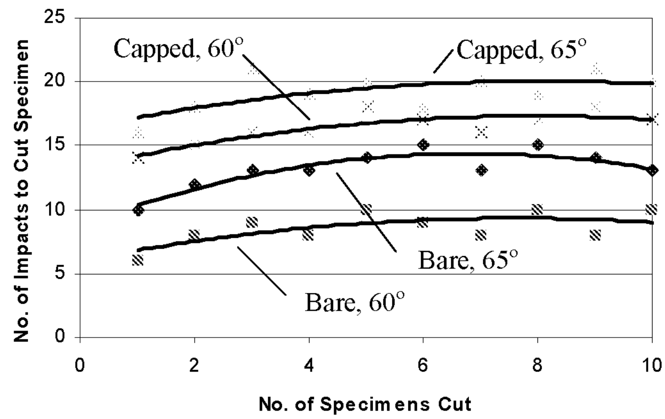


Figure 11. Number of impacts vs. chisel usage for various chisel configurations.

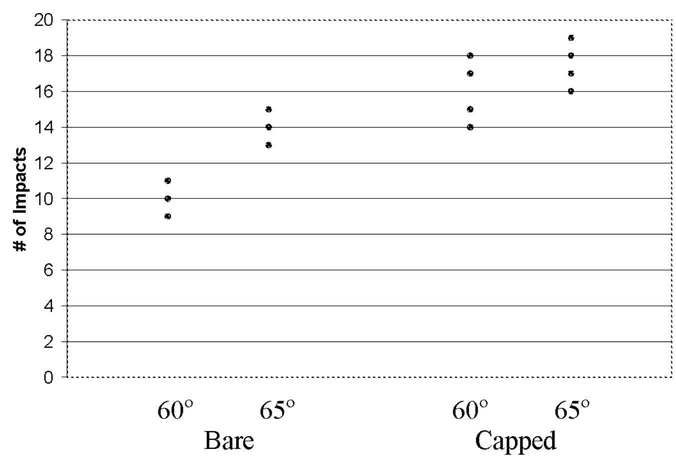


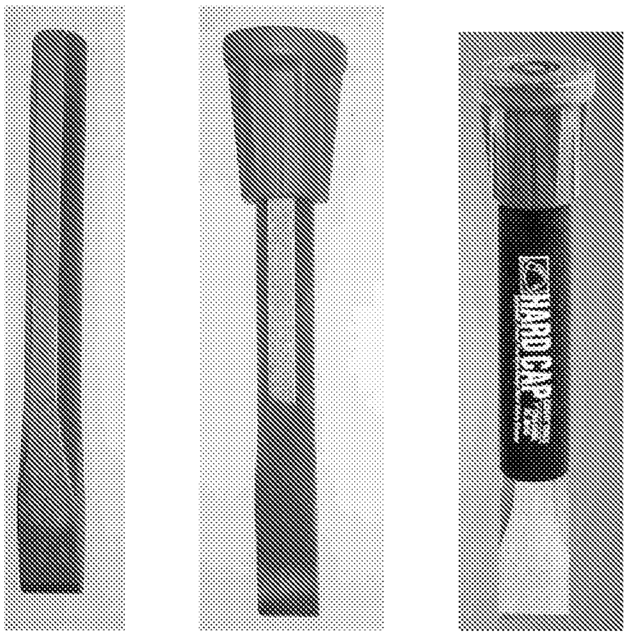
Figure 12. Measured number of impacts to cut the standard test specimen for various chisel configurations.

distortion, or wear. The effects of miss-hits and off-center hits are currently under investigation.

MEASSUREMENT OF VIBRATION AND SOUND EMISSIONS

Experimental Treatments.

To evaluate the potential effects of the polymer cap on vibration and noise emissions, prototype caps were injection molded and tested. Figure 13a and 13b show typical conventional and polymer capped metal cutting chisels, respectively, used in this study. In addition, a third chisel treatment was included in which a common urethane grip was placed around the shank of the chisel were the user grips the tool (Figure 13c).



(a) Bare Chisel (b) Polymer Capped Chisel (c) Polymer Capped w/ Urethane Grip

Figure 13. Chisel treatments evaluated in this study.

Instrumentation and Data Acquisition

Vibration measurements were made at the pneumatic chisel handle-hand interface using a PCB Piezotronics Tri-Axial Accelerometer (Model SEN021F) with a nominal sensitivity of 10 mV/g and a frequency response range of 1-10000 Hz. A small mounting fixture was used to position the accelerometer along the hand. Signal conditioning was performed with a PCB Piezotronitcs Model 480B21 Three-Channel Conditioner. A LinearX 150 mm diameter precision acoustic measurement microphone (Model M51A) with an acoustic sensitivity of 11.086 mV/94.00 dBspl was used for all tests. A DC supply of 9 volts powered the calibrated microphone and a National Instruments Data Acquisition Card (E-Series, PCMCIA 16-bit) and laptop computer were used to record the sound signal along with the vibration signals.

A *LabVIEW* program was written to interface to the A/D board and collect data as well as process, analyze and log the acquired signals (Figure 19). The averaged level of the sound pressure signal was computed based on an exponential mode after each sample of time and returned as an exponential averaged sound level in decibels. Selecting a custom exponential time constant of 125 milliseconds allowed for the continuous running average to accurately capture a short duration impulsive signal. Discrete Fourier transforms of the sound pressure and acceleration were performed using the following form:

$$F_n = \sum_{k=0}^{N-1} f(n) e^{i 2\pi nk/N}$$

where,

F_n = Fourier transform
$f(n)$ = n^{th} measured time domain data
N = Number of data

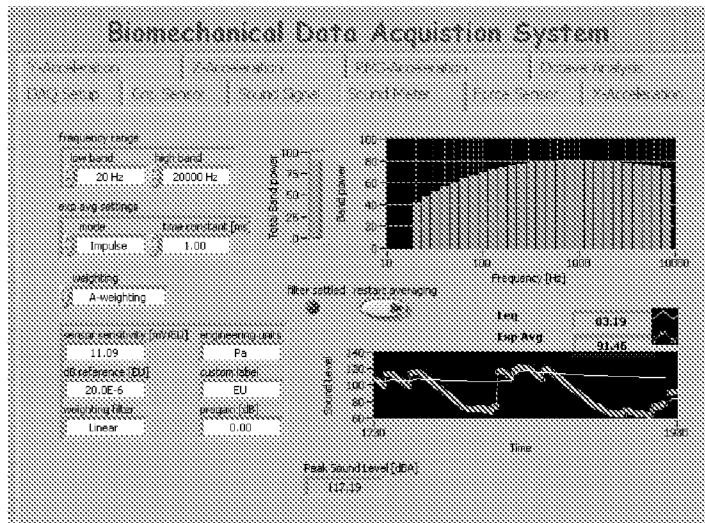


Figure 14. *LabVIEW* interface for the data acquisition and processing program used to collect and analyze the sound and vibration data.

Sound Measurements.

Tests were conducted to compare sound emissions from bare and capped chisels. On average, the peak sound pressure from a bare chisel was significantly higher than the capped chisel treatments. Figure 15 contains sound emission (pressure) vs. time for each treatment shown in Figure 13. The corresponding frequency spectra for each plot in Figure 15 is provided in Figure 16. The bare chisel produced distinct sounds between 4500 and 5000 Hz. In comparison, the capped chisel and capped chisel and urethane grip both significantly reduced the sound energy in this range.

Both the reduction in sound pressure across all sound frequencies and the suppression of certain sound frequencies achieved with the addition of the cap are significant. Human ears are particularly susceptible to hearing damage from noise at high frequencies, especially when exposed for extended periods of time. The beneficial effects of the polymer cap regarding noise suppression will substantially reduce the potential for hearing damage resulting from long term tool use and noise exposure.

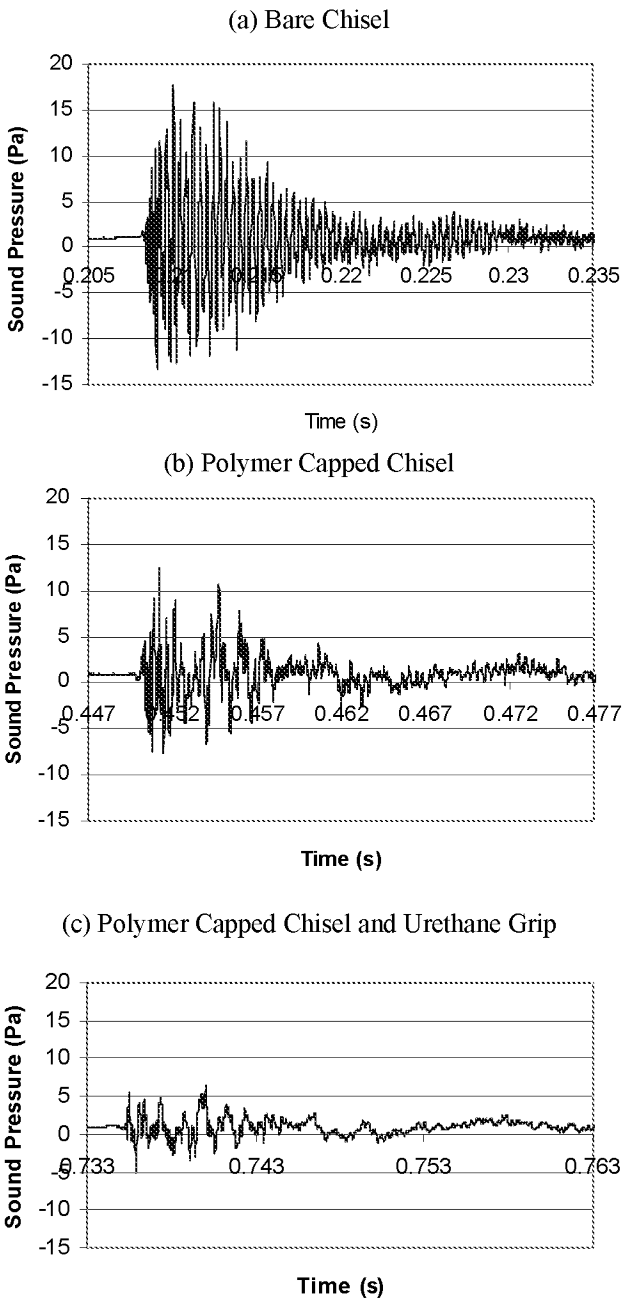


Figure 15. Typical sound pressure emission from a single impact with a (a) bare, (b) capped, and (c) capped chisel with protective grip.

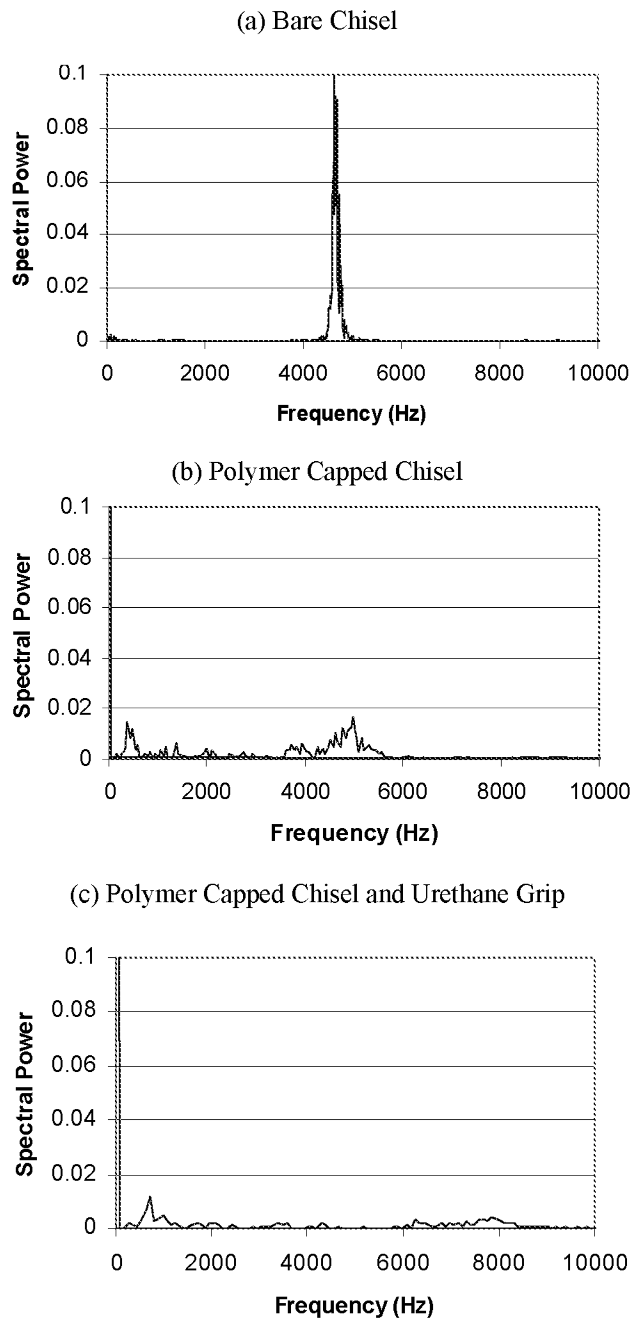


Figure 16. Typical frequency spectrums for a (a) bare, (b) capped, and (c) capped chisel with protective grip.

Vibration Measurements

Vibration measurements were made at three locations (palm, wrist, elbow), each with triaxial accelerometers. The vector sums were computed at each location. Three different users were tested using each chisel treatment, and ten replicates were recorded. Tests were performed in random order.

Table 1 contains peak acceleration values for each treatment. Values shown are an average of the ten replicates. The addition of a cap significantly reduced peak vibration levels compared to a bare chisel at the palm, wrist and elbow. The addition of the urethane grip did significantly reduced vibration at the elbow and wrist. Surprisingly, the addition of

the grip increased tool vibration at the palm. This is most likely the result of the added compliance provided by the grip, and the resulting larger displacements of the tool.

Typical acceleration vs. time plots at the wrist are provided in Figure 16, and illustrate the reductions in accelerations associated with the addition of the cap.

Table 1. Summary of average peak vector sum of x,yx vibration for each chisel treatment. Units are in g's.

	Bare Chisel	Polymer Cap Only	Polymer Cap and Grip
Palm	6380	3214	3648
Wrist	89.5	17.2	7.4
Elbow	3.5	1.8	1.6

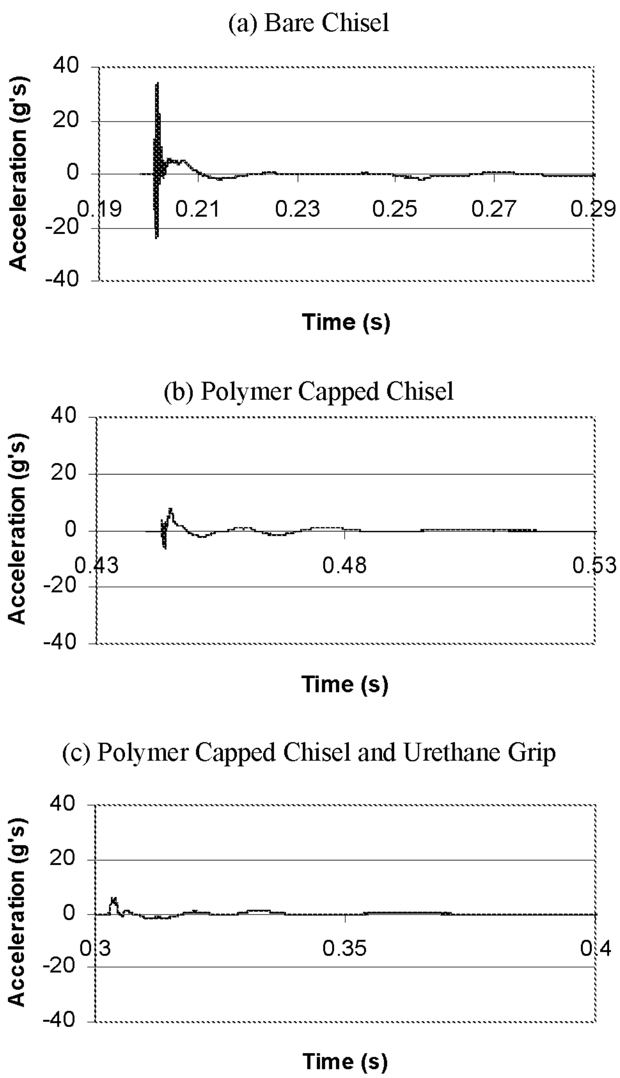


Figure 17. Wrist vibration for a (a) bare, (b) capped, and (c) capped chisel with protective grip.

CONCLUSIONS

Based on the results of this study, the following conclusions have been made:

- The testing methodology was effective in comparing different materials, configurations, etc. for chisel designs that incorporate engineering polymers. The key measures of performance are first the number of hits to fail a standard rod, and second, the chisel force exerted on the test specimen.
- The force transmission characteristics of the hammer-chisel-work system can be modeled with a relatively simple lumped parameter model. Using a series of springs and masses to represent the hammer, chisel, and work, a system model was developed, validated, and used to predict chisel force exerted on the work, and optimize cap thickness and material selection.
- The ideal material for a cap is a polymer with high modulus - to transmit a high force, and high impact strength - to withstand repeated blows.
- Chisel vibration resulting from a hammer impact was generally found to be very high. The addition of the cap significantly reduced vibration levels at the palm, wrist and elbow.
- Chisel noise emission was altered with the addition of the polymer cap. Sound emission around 4500 to 5000 Hz was significantly reduced the addition of the cap.
- Cyclic impact tests of a polymer capped chisel indicate that the tool can be struck thousands of times without failure or undo wear. The effect of off-center and missed hits are currently being investigated.
- Performance of capped chisels is somewhat lower than bare chisels. However, this effect can be essentially eliminated by using a sharper chisel tip angle.
- Polymer capped chisels have several significant performance advantages: reduced operator discomfort due to hand-arm mechanical shock, reduced noise, and less danger from flying metal fragments.

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